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A Holistic Abundance Analysis to r-rich Stars

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ABSTRACT
The chemical abundances of the metal-poor star are an excellent test bed to set new constraints on models of neutron-capture processes at low metallicity. Some r-rich metal-poor stars, such as HD 221170, show overabundance of the heavier neutron-capture elements and excesses of lighter neutron-capture elements. The study for these r-rich stars could make us get a better understanding of weak r- and main r-process nucleosynthesis at low metallicity. Based on the conclusions of the observation of metal-poor stars and neutron-capture element nucleosynthesis theory, we set up a model to determine the relative contributions from weak r- and main r-process to the heavy element abundances in metal-poor stars. Using this model, we find that the abundance patterns of light elements for most sample stars are close to the pattern of the weak r-process star, and heavier neutron-capture elements is very similar to main r-process star, while the lighter neutron-capture elements can be fitted by mixing of weak r- and main r-process material. The production of the weak r-process elements appears to be associated with the light elements and the production of main r-process elements are almost decoupled from that of the light elements. We compare our results with the observed data at low metallicities, showing that the predicted trends are in good agreement with the observed trends, at least for the metallicity range [Fe/H]<-2.1. For most of sample stars, the abundance pattern of both neutron-capture elements and light elements could be best explained by a star formed in a molecular cloud that had been polluted by both weak r- and main r-process material.

Key words: stars: weak r-process fraction, stars: abundances, nucleosynthesis

1 INTRODUCTION

The elements heavier than the iron peak are made through neutron capture via two principal processes: the r-process and the s-process (Burbidge et al. 1957). Observational evidence and theoretical studies have identified the main s-process site in low- to intermediate-mass ($\approx 1.3-8M_{\odot}$) stars in the asymptotic giant branch (AGB) (Busso et al. 1999). The r-process is usually associated with the explosive environment of Type II supernovae (SNeII), although this astrophysical site has not been fully confirmed yet (Arnould et al. 2007, Sneden et al. 2008). The abundances of neutron-capture elements and other light elements in metal-poor halo stars are now providing important clues to the chemical evolution and early nucleosythesis history of the Galaxy.

The process producing heavier r-process elements ($Z \geqslant 56$, i.e., heavier than Ba) is referred to as main r-process (e.g., Truran et al. 2002; Wanajo & Ishimaru 2006). The observations in the ultra-metal-poor halo star CS 22892-052 (Sneden et al. 2003) and CS 31082-001(Hill et al. 2002; Honda et al. 2004; Plez et al. 2004; Barklem et al. 2005; Spite et al. 2005) revealed that the abundances of the heavier stable neutron-capture elements are in remarkable agreement with the scaled solar system r-process pattern, called as "main r-process stars" (Sneden et al. 2003). More recent work , utilizing updated experimental atomic data to determine more accurate abundances, has confirmed this agreement (Sneden et al. 2009). Since they are thought to exhibit the abundance pattern produced by a single or at most a few r-process events in the early Galaxy, the stability of the observed abundance pattern of neutron-capture elements and the good agreement with the solar system heavier r-process contribution imply that main r-process events generate a universal abundance distribution. Because the strong enhancements of heavier r-process elements relative to iron and other light elements, it is believed that the production of main r-process elements is fully decoupled from that of Fe and all other light elements between N and Ge (Qian & Wasserburg 2007). However, these objects show some deficiencies in lighter neutron-capture elements ($37 \leqslant Z \leqslant 47$, i.e., from Rb to Ag) compared to the scaled solar r-process curve (e.g., Sneden et al. 2000; Hill et al. 2002). This means that the r-process abundance pattern in solar-system material is not fully explained by the component that makes the pattern found in such main r-process-enhanced stars, but another neutron-capture process referred sometimes as "LEPP" (lighter element primary process) or "weak r-process" is required (Travaglio

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et al. 2004; Wanajo & Ishimaru 2006). In addition to the neutron-capture elements abundance distribution, observations of other elemental abundances in unevolved metal-poor halo stars can also provide important clues about nucleosynthesis events in the early Galaxy. These stars are old and preserve in their photospheres the abundance composition at the location and time of their formation. Thus, the abundances of the light elements in main r-process stars should reveal the composition of interstellar medium (ISM) at the location and time of their formation.

The moderate enhancements of Eu and other r-process elements relative to iron have been observed in normal metal-poor stars, which means that the abundance of Eu ([Eu/Fe]≈0.3) is enhanced moderately in ISM (Fields et al 2002). However, some very metal-poor stars, such as HD 122563, have excesses of lighter neutron-capture elements Sr, Y, and Zr, while their heavier ones (e.g., Ba, Eu) are very deficient ([Eu/Fe]≈ -0.5) (McWilliam 1998; Johnson 2002; Aoki et al. 2005; Honda et al. 2004, 2006, 2007; Spite et al. 2005; Andrievsky et al. 2007). Such objects possibly record the abundance patterns produced by another component and are called as "weak r-process stars" (Izutani et al. 2009). In HD 122563, the abundances of neutron-capture elements continuously decrease with the increase of atomic number and the lighter neutron-capture elements with intermediate mass elements show moderate enhancements with respect to heavier ones. This is the first determination of the overall abundance pattern that could represent the yields of the weak r-process. Recently, Honda et al. (2007) showed another example of the weak r-process stars HD 88609, and concluded that the abundance pattern of neutron-capture elements in HD 88609 is quite similar to HD 122563. However, the similarity of the abundance pattern found in the two objects can not be interpreted as uniqueness of the pattern produced by the weak r-process (or LEPP), because the two objects were selected to have similarly high Sr/Eu abundance ratios. In the cloud polluted by weak r-process, [Eu/Fe]≈ -0.5 means that the production of Fe group and other light elements is decoupled from heavier r-process elements, while [Sr/Fe]≈ 0 implies that the weak r-process elements are produced in conjunction with the Fe and light elements. Thus, the abundances of both lighter neutron-capture and light elements in weak r-process stars should reveal the composition of the cloud polluted by weak r-process event. In this case, the holistic abundance pattern including both the light and weak r-process elements should be considered.

Based on observations of metal-poor stars having different Sr/Eu ratios, Montes et al.(2007) concluded that the weak r-process produces a uniform and unique abundance pattern of neutron-capture elements. They found that the uncertainties on the weak r-process pattern obtained are smaller for stars with significant weak r-process contribution, such as HD 122563 and HD 88609, but larger for higher [Eu/Fe]. When [Eu/Fe] reaches 0.8, the uncertainties will reach about 1.0 dex (see Figure 3 in Montes et al. 2007). Therefore to obtain more information about weak r-process, one needs to investigate the stars with the moderate overabundance in [Eu/Fe] where both the weak r- and main r-process do not prominently dominate the composition. Especially, the moderate r-process enhanced metal-poor stars with [Eu/Fe]$\gtrsim$0.5 should be very important for this topic.

Recently, Ivans et al. (2006) analyzed the spectra of the metal-poor star HD 221170 ([Eu/Fe]=0.8). Surprisingly, in contrast to the abundance patterns of other main r-process stars, the abundances of HD 221170 do not show the pronounced underproduction of lighter r-process elements as seen in other main r-process enhanced stars, and could be well fit by solar r-process abundance pattern. The [Eu/Fe] of HD 221170 is 0.8, which just means that the weak r-process do not prominently dominate the composition. There have been many theoretical studies of r-process nucleosynthesis. Unfortunately, the precise r-process nucleosynthesis sites or what the sites for these various mass ranges of neutron-capture elements observed in the halo stars are still unknown. As the abundances of the metal-poor halo stars can be applied as a probe of the conditions of r-process nucleosynthesis in the early Galaxy, clearly, the holistic analysis of both neutron-capture and other light elemental abundances in HD 221170 and other metal-poor stars is very important for a good understanding of the neutron-capture nucleosynthesis in the early Galaxy. These reasons motivated us to investigate the holistic element abundance patterns in the metal-poor r-process-rich (hereafter r-rich) stars, in which light elements, lighter and heavier neutron-capture elements are observed.

In this paper, we study elemental abundances of 14 metal-poor stars, in which more than about 20 elements have been observed. Firstly, we extend the abundance pattern of main r-process and weak r-process to light elements. Then, we investigate the characteristics of the nucleosynthesis that produces the abundance ratios of these stars using the weak r- and main r-process parametric model. In Sect. 2 we extracted the abundance clues about weak r- and main r-process from the metal-poor star HD 2221170. The parametric model of metal-poor stars is described in Sect. 3. The calculated results are presented in Sect. 4 which we also discuss the characteristics of the weak r- and main r-process nucleosynthesis. Conclusions are given in Sect. 5.

2 ABUNDANCE CLUES

Recent observations and the analyses imply that the abundance pattern of an extremely metal-deficient star with [Fe/H]$\leqslant -2.5$ may retain information of a preceding single supernova (SN) event or at most a few SNe (Mcwilliam et al. 1995; Ryan et al. 1996). It is important to simultaneously analyse the observed light and heavy elements to study the physical conditions that could reproduce the observed abundance pattern found in metal-poor stars. As an example, we investigate the observed elemental abundance pattern of metal-poor HD 221170 (Ivans et al. 2006).

Figure 1 shows the abundance comparisons of the abundance pattern of HD 221170 with that of the weak r-process star HD 122563 and the main r-process star CS 31082-001 in the logarithmic scale. The abundances of CS 31082-001 are normalized to Eu, which is predominantly an r-process element. For the two stars, HD 221170 and CS 31082-001, shown in this figure, have almost identical abundance pattern from Ba to Ir, but the light elements, such as N, O, Mg and Fe group, differ greater than 0.5 dex, which indicates that the origin of light elements and main r-process is seemly different. Because the excess of light elements for HD 221170, could not be fitted simultaneously by the abundances of main r-process star, we can conclude that the production of light elements should not accompany with the production of the heavier r-process elements, which is similar to the abundance characteristic of main r-process stars (Qian & Wasserburg 2007). On the other hand, we take HD 122563 as a weak r-process star (Honda et al. 2006), and plot its observed element abundances normalized to Fe, because Fe group elements are produced in conjunction with the weak r-process. Our conclusion here is that the abundance pattern of light elements in HD 221170 is quite similar to that of HD 122563, although a small difference is suggested. In summary, we have found that the abundance pattern of HD 221170 can be fitted partly by

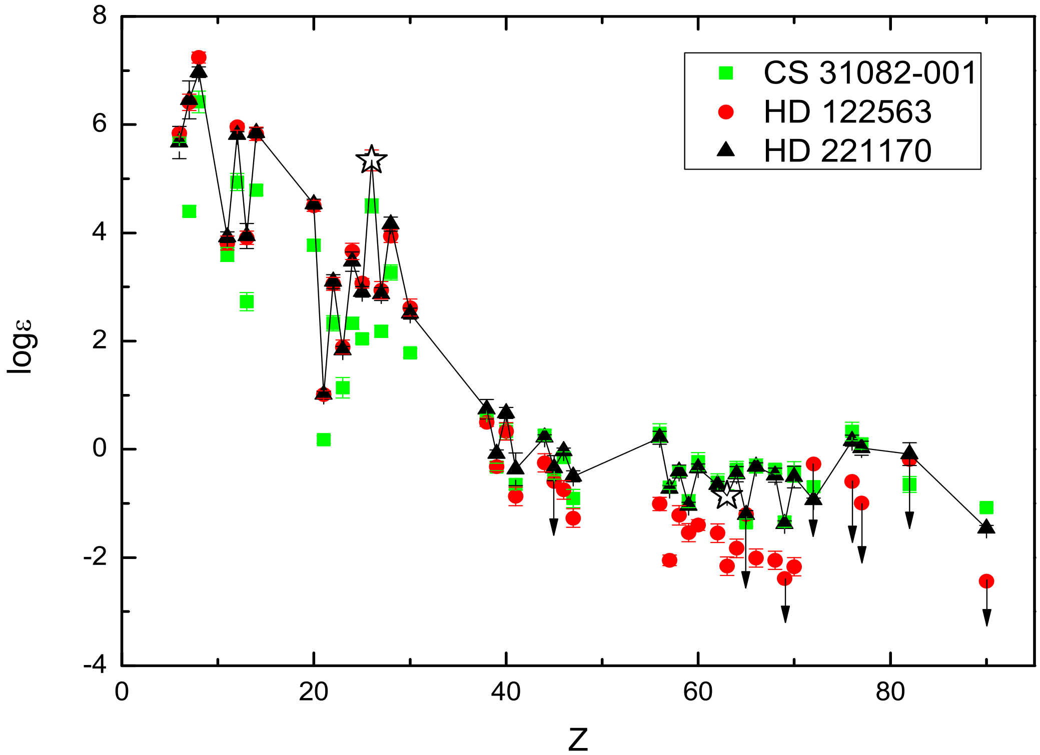

Figure 1. Abundance pattern of HD 221170, scaled abundance pattern obtained by main r-process star CS 31082-001, and scaled abundance pattern obtained by weak r star HD 122563. The CS 31082-001 was normalized to the Eu abundance while HD 122563 was normalized to the Fe abundance. The scaled Fe and Eu have been denoted specifically by open stars.

abundance curves from the weak r-process stars and the main r-process stars. Obviously, a precise calculation is needed.

3 PARAMETRIC MODEL OF METAL-POOR STARS

We note that considering the larger overabundance of Eu to Fe for main r-process star and deficient of Eu to Fe for weak r-process star, the origins of the light elements in two stars are clearly different. For main r-process stars, the light elements mainly come from the cloud in which the star formed, while for weak r-process stars, the light elements mainly come from the production in conjunction with the weak r-process. Since the main r-process are not sufficient to explain the observed abundances in HD 221170 and some other metal-poor stars, another component that yields both lighter neutron-capture elements and light elements is required. We assume that all of the r-process abundances come from two r-processes, each with a different set of abundance signatures. It is interesting to adopt the two r-processes components parametric model to study the relative contributions from the weak r- and main r- processes that could reproduce the observed abundance pattern found in r-rich stars. For this purpose, we propose that the ith element's abundance in this star can be calculated as follows:

$$N_i = C_w^{'} N_{i,\, rw} + C_m^{'} N_{i,\, rm}, \tag{1}$$

where $N_{i,\, rw}$ is the abundance of the ith element produced by the weak r-process and $N_{i,\, rm}$ is the abundance of the ith element produced by the main r-process, and $C_w^{'}$ and $C_m^{'}$ are the component coefficients that correspond to contributions from the weak r-process and the main r-process, respectively.

The ultra-metal-poor stars CS 22892-052 and CS 31082-001 merit special attention, because these two stars have extremely large over abundances of neutron-capture elements relative to iron and very low metallicity with [Fe/H]~ -3. Many studies (Cowan et al. 1999; Sneden et al. 1996, 1998, 2000) have suggested that the abundance patterns of the heavier stable neutron-capture elements in these stars are consistent with the solar system r-process abundance distribution. However, this concordance breaks down for the lighter neutron-capture elements (Sneden et al. 2000). These two stars could have abundances that reflect results of the pure main r-process nucleosynthesis of a single SN, so the adopted abundances of nuclei $N_{i,\, rm}$ in equation (1) are taken from the average abundances of CS 22892-052 and CS 31082-001, which is normalized to the Eu abundance of CS 22892-052. Metal-poor stars with very low Eu abundance play an essential role in constraining the weak r-process as they have the smallest contribution from the main r-process. According to Montes et al. (2007), we can obtain the weak r-process abundance pattern using average abundance of HD 122563 and HD 88609 to subtract the main r-process abun-

dance pattern, normalized to Eu. This means that all Eu is made in the main r-process.

From consideration of the observed abundances in metal-poor stars, it is proposed that the sources for main r-process also produce some lighter r-nuclei (e.g., Sr, Y, and Zr) and the production of main r-process nuclei is not related to the production of Fe group elements and other elements with lower atomic numbers: O, Na, Mg, Al, Si, Ca, Sc, and Ti. However, the production of the weak r-process elements appears to be associated with that of Fe group elements and other light elements (Qian & Wasserburg 2007). Thus, we also attempt to investigate the abundance pattern of light elements in r-rich stars utilizing equation (1). Based on the abundances of two weak r-process stars and two main r-process stars, we extended the abundances $N_{i,rm}$ and $N_{i,rw}$ to light elements, except C and N, because these two elements may have another origin in CS 22892-052 (Masseron et al. 2010). Our goal is to find the parameters which best characterize the observed data. The reduced χ^2 is defined:

$$\chi^2 = \sum \frac{(N_{obs} - N_{cal})^2}{(\triangle N_{obs})^2 (K - K_{free})}, \quad (2)$$

whereΔN_{obs} is the uncertainty on the observed abundance, K is the number of elements applied in the fit, and K_{free} is the number of free parameters varied in the fit. Based on equation (1), we carry out the calculation including the contributions of the weak r- and main r- processes to fit the abundance profile observed in HD 221170 and other metal-poor stars, in order to look for the minimum χ^2 in the two parameter space formed by $C_w^{'}$, and $C_m^{'}$.

4 RESULTS AND DISCUSSION

4.1 Calculated Results

Using the observed data in 14 sample stars including CS 22892-052, CS 31082-001, HD 122563 and HD 88609 (Westin et al. 2000; Cowan et al. 2002; Hill et al. 2002; Sneden et al. 2003; Honda et al. 2004, 2006, 2007; Barklem et al. 2005; Ivans et al. 2006; Christlieb et al. 2008; Hayek et al. 2009; Roederer et al. 2010), the model parameters can be obtained. The results of the [Fe/H], [Eu/Fe], [Sr/Fe], [Sr/Eu], the component coefficients and χ^2 are listed in Table 1.

Figure 2 shows our calculated best-fit results. In order to facilitate the comparisons of the predicted abundances with the observations, the element observed abundances are marked by full circles. For most stars, it can be seen that in consideration of the observational errors, there is good agreement between the predictions and the data for all elements starting with O to Pb in sample stars. In the top panel of Figure 3, we show individual relative offsets ($\triangle log\varepsilon$) for the sample stars with respect to the predictions from the parametric model. Typical observational uncertainties in $log\varepsilon$ are $\sim 0.2-0.3$ dex (dotted lines). It is clear from the Figure 2 and 3 that the elemental abundances are in agreement for all sample stars, and they follow closely the calculated curve. The root mean square offset of these elements in $log\varepsilon$ shown in bottom panel is mostly smaller than 0.20 dex for the comparison with the predictions. This value is consistent with zero, given the combined uncertainties in stellar abundances and predicted abundances, confirming the validity of the parametric model adopted in this work.

It is interesting to notice from these Figure 2 and 3 that the model predictions are as well for the lighter neutron-capture elements as heavier neutron-capture elements, especially for Sr, Y, and Zr. This means that the weak r-process abundance pattern for $38 \leqslant Z \leqslant 47$ adopted in this work is remarkably stable from star-to-star, though the overall level of enrichment with respect to iron (e.g., [Eu/Fe]) shows a very large star to star scatter. The very large scatter of [Eu/Fe] from star-to-star implies that very metal-poor halo stars sample a largely unmixed early Galaxy. Since these stars are thought to exhibit the abundance pattern produced by a single or at most a few r-process events in the early Galaxy, the stability of the observed abundance pattern and the good agreement with the calculated results imply that not only main r-process events generate a stable abundance distribution but also weak r-process events create another universal abundance distribution.

4.2 Example: HD 221170

As an example, it is interesting to investigate a possible explanation of the parameters obtained for a r-rich star HD 221170 using parametric model. Main r-process mainly occurs in the SNe explosion of $\sim 8-11 M_\odot$ stars (Qian & Wasserburg 2007, Wanajo, & Ishimaru 2006) and the weak r-process may occur in the Fe core-collapse SNe explosion of $\sim 12-25 M_\odot$ massive stars (Izutani et al. 2009). So these two processes can produce a significant fraction of the heavy element abundances in early times of the Galaxy. We notice from Table 1 that the component coefficients of weak r- and main r-process for HD 221170 are $C_w^{'} = 3.755$, $C_m^{'} = 0.612$, respectively, which implies that this star is not “pure” main r-process star or “pure” weak r-process star. For most of the sample stars, we can obtain the similar result as that of HD 221170, except five stars, which are main r-process stars (i.e., CS 22892-052, CS 29497-004 and CS 31082-001) or weak r-process stars (i.e., HD 122563 and HD 88609).

It was possible to isolate the contributions corresponding to the weak r- and main r-process by our parametric model. Taking the values of $C_w^{'}$, and $C_m^{'}$ into Eq. (1), the abundances of all the neutron-capture elements in HD 221170 are obtained as listed in Table 2. Columns (3), (4), and (5) of Table 2 give the total abundances, the weak r-process component, and the main r-process component in this halo star, respectively. In columns (6) and (7), we list the weak r- and main r-process fractions (or associated with the weak r- and main r-process) to the total abundances, these values are useful in understanding the relative contributions of two processes for a given neutron-capture or light element in HD 221170. The Sr and Eu abundances are most useful for unravelling the sites and nuclear parameters associated with the weak r- and main r-process correspond to those in extremely metal-poor stars (Francois et al. 2007), polluted by material with a few times of nucleosynthetic processing. An interesting question is the behavior of lighter r-process elements below Ba. In the weak r-process star HD 122563 based on our model, the elemental abundances of Sr, and Eu (the representative for pure main r-process elements) consist of significantly different combinations of weak r- and main r- process contributions, with r-weak:r-main ratios for Sr and Eu of 93:7 and 0:1, respectively. We explored the contributions of weak r- and main r-process for Sr in HD 221170. Clearly, for the star listed in Table 2, the r-weak:r-main ratio for Sr is 47:53, which is smaller than the ratio in HD 122563. The Sr abundances of HD 221170 is a result of pollution from the two r-processes material of the former SNe. It is suggested that even though the main r-process is dominantly responsible for synthesis of the lighter neutron-capture elements for this star, the contributions from the weak r-process to lighter neutron-capture elements are not negligible at all, such as

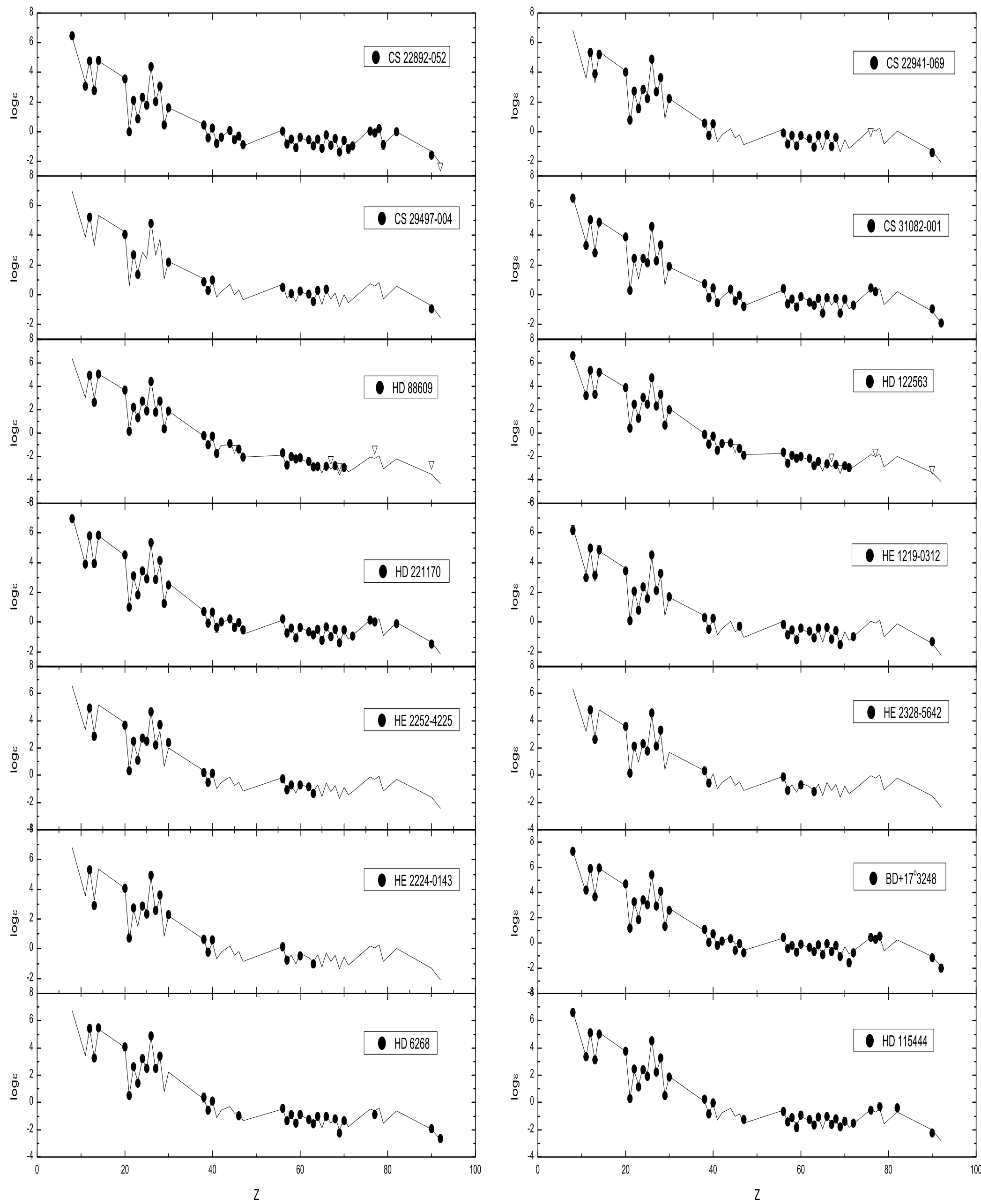

Figure 2. Comparison of the observed elemental abundances for 14 sample stars with the elemental abundances calculated by this model. The full circles with appropriate error bars denote the observed element abundances and the solid lines are the predicted elemental abundance curves. Upper limits are indicated by downward-facing open triangles.

Table 1. Observed Abundance Ratios and the Derived Parameters for the sample Stars

stars	[Fe/H]	[Eu/Fe]	[Sr/Fe]	[Sr/Eu]	C'_w	C'_m	C_w	C_m	χ^2
HD 221170	-2.18	0.80	0.02	-0.78	3.755	0.612	8.624	6.147	1.298
HE 1219-0312	-2.96	1.38	0.35	-1.03	0.086	0.512	1.190	30.985	0.755
CS 31082-001	-2.91	1.63	0.65	-0.98	0.009	0.953	0.111	51.402	0.434
CS 29497-004	-2.63	1.68	0.55	-1.13	0.000	2.364	0.000	66.917	1.130
CS 29491-069	-2.51	0.96	0.15	-0.81	1.210	0.651	5.942	13.979	1.179
HD 115444	-2.98	0.85	0.32	-0.53	0.676	0.126	9.796	7.985	1.539
BD +17°3248	-2.08	0.91	0.29	-0.62	4.315	1.152	7.872	9.191	0.903
CS 22892-052	-3.10	1.64	0.58	-1.06	0.000	0.589	0.000	49.204	0.725
HD 6268	-2.63	0.52	0.07	-0.45	1.438	0.147	9.308	4.161	0.933
HD 122563	-2.77	-0.52	-0.27	0.25	1.166	0.006	10.419	0.234	0.657
HD 88609	-3.07	-0.33	-0.05	0.28	0.712	0.004	12.694	0.312	1.125
HE 2224+0143	-2.58	1.05	0.23	-0.82	1.027	0.671	5.925	16.928	0.455
HE 2252-4225	-2.82	0.99	0.06	-0.93	0.728	0.317	7.299	13.898	0.739
HE 2327-5642	-2.93	1.22	0.31	-0.91	0.189	0.384	2.441	21.688	0.353

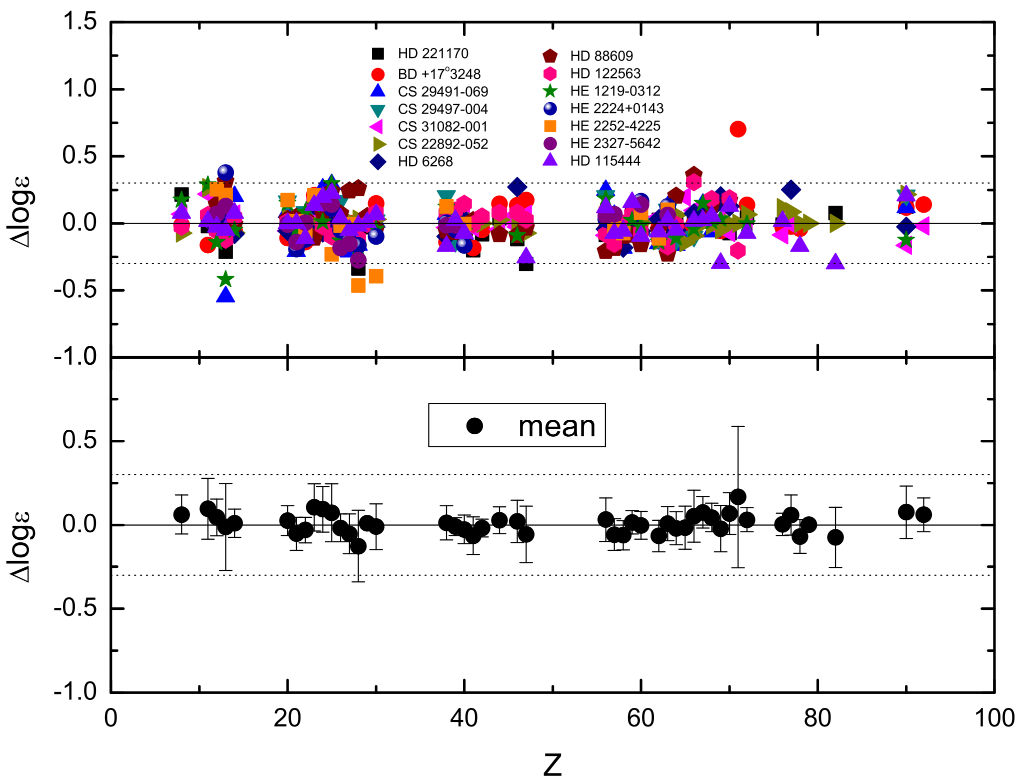

Figure 3. In the top panel, difference plot showing the individual elemental abundance offsets for each of the 14 stars with respect to the calculated values. Zero offset is indicated by the dashed horizontal line. The bottom panel displays average stellar abundance offsets.

Sr, Y and Zr. For this sample star, the heavier neutron-capture elements are predominated, within the observational errors, by main r-process because the r-weak:r-main ratios are mostly smaller than 10:90. The agreement of the model results with the observations for heavier neutron-capture elements indicates that the heavier elements are produced by the main r-process that produces a universal abundance pattern with fixed element ratios consistent with the solar r-process abundance pattern. This is a similar conclusion that has been drawn from the abundance pattern of the few very metal-poor, strongly main r-process-enhanced stars where a large range of elemental abundance has been determined (see, e.g., the reviews by Truran et al. 2002; Cowan et al. 2006). It is obvious from Table 2 that the lighter r-process elements behave very differently to heavier elements. Clearly, for the star listed in Table 2, the r-weak:r-main ratios from Sr through Ag are larger than 20:80, which are larger than the ratios of the heavier r-process elements. Because the

Table 2. The weak r- and main r-process elemental abundances of HD 221170

Element	Z	N_{total}	$N_{i,rw}^{star}$ or associated r-weak	$N_{i,rm}^{star}$ or associated r-main	$f_{r,weak}$ or associated r-weak	$f_{r,main}$ or associated r-main
O	8	4.43E+05	3.72E+05	7.15E+04	0.839	0.161
Na	11	2.29E+02	1.68E+02	6.07E+01	0.735	0.265
Mg	12	2.01E+04	1.82E+04	1.87E+03	0.907	0.093
Al	13	1.54E+02	1.39E+02	1.52E+01	0.901	0.099
Si	14	1.87E+04	1.71E+04	1.65E+03	0.912	0.088
Ca	20	8.60E+02	7.40E+02	1.20E+02	0.861	0.139
Sc	21	2.64E-01	2.33E-01	3.08E-02	0.883	0.117
Ti	22	3.11E+01	2.69E+01	4.26E+00	0.863	0.137
V	23	2.80E+00	2.58E+00	2.22E-01	0.921	0.079
Cr	24	1.04E+02	9.88E+01	5.58E+00	0.947	0.053
Mn	25	2.34E+01	2.13E+01	2.12E+00	0.909	0.091
Fe	26	5.63E+03	4.90E+03	7.28E+02	0.871	0.129
Co	27	1.89E+01	1.56E+01	3.25E+00	0.828	0.172
Ni	28	1.92E+02	1.54E+02	3.87E+01	0.799	0.201
Cu	29	5.03E-01	4.18E-01	8.45E-02	0.832	0.168
Zn	30	1.27E+01	1.14E+01	1.25E+00	0.901	0.099
Sr	38	1.72E-01	8.12E-02	9.05E-02	0.473	0.527
Y	39	2.41E-02	1.32E-02	1.09E-02	0.549	0.451
Zr	40	1.22E-01	6.65E-02	5.51E-02	0.547	0.453
Nb	41	7.75E-03	2.89E-03	4.86E-03	0.373	0.627
Mo	42	2.57E-02	1.38E-02	1.19E-02	0.536	0.464
Ru	44	5.24E-02	1.42E-02	3.82E-02	0.270	0.730
Rh	45	<1.46E-02	<7.02E-03	7.58E-03	<0.481	>0.519
Pd	46	2.05E-02	4.99E-03	1.56E-02	0.243	0.757
Ag	47	4.54E-03	1.20E-03	3.34E-03	0.264	0.736
Ba	56	3.84E-02	5.34E-04	3.79E-02	0.014	0.986
La	57	4.31E-03	2.87E-05	4.28E-03	0.007	0.993
Ce	58	9.91E-03	8.52E-04	9.06E-03	0.086	0.914
Pr	59	3.14E-03	7.00E-04	2.44E-03	0.223	0.777
Nd	60	1.33E-02	3.76E-04	1.29E-02	0.028	0.972
Sm	62	6.71E-03	3.02E-04	6.41E-03	0.045	0.955
Eu	63	3.36E-03	0.00E+00	3.36E-03	0.000	1.000
Gd	64	1.04E-02	0.00E+00	1.04E-02	0.000	1.000
Tb	65	1.60E-03	0.00E+00	1.60E-03	0.000	1.000
Dy	66	1.43E-02	0.00E+00	1.43E-02	0.000	1.000
Ho	67	3.60E-03	0.00E+00	3.60E-03	0.000	1.000
Er	68	9.82E-03	0.00E+00	9.82E-03	0.000	1.000
Tm	69	1.15E-03	0.00E+00	1.15E-03	0.000	1.000
Yb	70	7.53E-03	0.00E+00	7.53E-03	0.000	1.000
Lu	71	2.03E-03	0.00E+00	2.03E-03	0.000	1.000
Hf	72	3.66E-03	0.00E+00	3.66E-03	0.000	1.000
Os	76	4.10E-02	0.00E+00	4.10E-02	0.000	1.000
Ir	77	2.90E-02	0.00E+00	2.90E-02	0.000	1.000
Pt	78	4.75E-02	0.00E+00	4.75E-02	0.000	1.000
Au	79	3.77E-03	0.00E+00	3.77E-03	0.000	1.000
Pb	82	2.80E-02	0.00E+00	2.80E-02	0.000	1.000
Th	90	1.33E-03	0.00E+00	1.33E-03	0.000	1.000
U	92	2.12E-04	0.00E+00	2.12E-04	0.000	1.000

Note—logε(El)=logN(El)+1.54

abundances of lighter neutron-capture elements are interpreted by the mixture of weak r- and main r-process, the agreement of the model results with the observations for the lighter elements implies that the weak r- process creates another universal and unique abundance pattern, which is consistent with the conclusion obtained by Montes et al. (2007).

It is important to simultaneously analyse the observed light elements and neutron-capture elements to investigate the physical origins that could reproduce the abundance pattern of all observed elements in HD 221170. The associated r-weak:r-main ratios for the light elements from O to Zn are mostly larger than 80:20. This implies that the production of the weak r-process elements appears to be associated with that of Fe group elements and other light elements (e.g., Na, Mg, Al, Si, Ca, Sc, and Ti). By combining the analysis of neutron-capture elements, we find that the abundance pattern of light elements for HD 221170 is close to the pattern of the weak r-process star (e.g., HD 122563), and heavier r-process elements is very similar to main r-process star (e.g., CS 31082-001), while the lighter neutron-capture elements can be fitted by mixing of weak r- and main r-process material. The element abundance

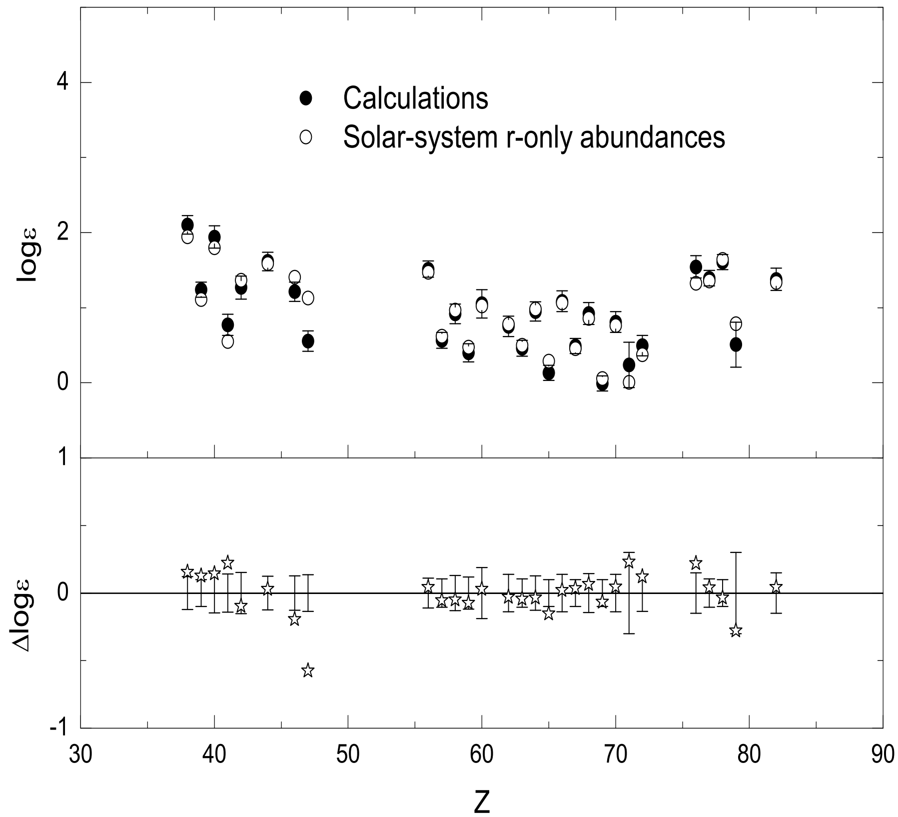

Figure 4. Comparison of the calculated $log\epsilon(X)$ abundances for $Z \geqslant 38$ and the solar r-process predictions from Arlandini et al.(1999). The bottom panel displays the difference defined as $\Delta log\epsilon(X) \equiv log\varepsilon(X)_{calc} - log\varepsilon(X)_{obs}$, where the error bars are the average observed error of four typical stars (CS 31082-001, CS 22892-052, HD 122563 and HD 88609).

pattern of HD 221170 can be explained by a star formed in a molecular cloud that had been polluted by both weak r-process and main r-process material. This implies that this star should be a "weak r + main r star".

4.3 Solar-system abundances and reduced component coefficients

Generally, the solar system abundances distribution is regarded as a standard pattern and the heavy element abundances of Population I stars are often expected to have the similar distribution, namely, $N_i = N_{i\odot} \times Z/Z_\odot$, where Z is the metallicity of stars. The neutron-capture element abundances in Solar-system material are sums of the two neutron-capture processes, knowing the s-process contributions allows the determination of the r-process contributions, or residuals, for individual isotopes (K$\ddot{a}$ppeler, Beer & Wisshak 1989, Arlandini et al. 1999, Cowan & Sneden 2006). By comparing the r-process elemental abundances in solar system material with the elemental abundances in metal-poor stars, we can determine the relative contributions from the weak r- and main r-process components to the synthesis of the neutron-capture elements in solar system and investigate some issues to neutron-capture nucleosynthesis at different metallicity. Therefore, we adopted equation (1) to fit solar system r-process abundances

$$N_{i,r,\odot} = C^{'}_{w,\odot} N_{i,\,rw} + C^{'}_{m,\odot} N_{i,\,rm}. \tag{3}$$

The main r-process pattern was normalized to the heavier neutron-capture elements from Eu to Pb in solar system abundance. And $C^{'}_{w,\odot}$ can be obtained by the lighter neutron-capture pattern. In Figure 4, the calculated results are compared with the solar system r-process abundances. For most elements, the calculations produced by the equation are agreement well with the r-process abundances of solar system (Arlandini et al. 1999). Thus, we can approximately adopt $C^{'}_{w,\odot} N_{i,\,rw}$ and $C^{'}_{m,\odot} N_{i,\,rm}$ to represent weak r-process component and main r-process component in solar system, respectively.

Based on our calculation, in the Sun, the elemental abundances of Sr, Y and Zr consist of similar combinations of weak r- and main r-process contributions, with r-week:r-main ratios for Sr, Y and Zr of 0.390:0.610, 0.464:0.536 and 0.462:0.538, respectively. The average ratio of Sr, Y and Zr is 0.788. The yield of Eu per main r-process event is estimated to be about $3 \times 10^{-7} M_\odot$ (Ishimaru et al. 2004). The yield of Sr per SN event due to the main r-process can be estimated to be $4.5 \times 10^{-6} M_\odot$, using the ratio of Sr/Eu (≈ 25, Sneden et al. 2003) in the main r-process star CS22892-052.

Clearly, the solar inventory is the result of contributions from many stellar sources over Galactic history. Due to mixing of nucleosynthetic products from different sources in the ISM over this long history, the patterns for the gross abundances of a wide range of elements in other stars with approximately solar metallicity are

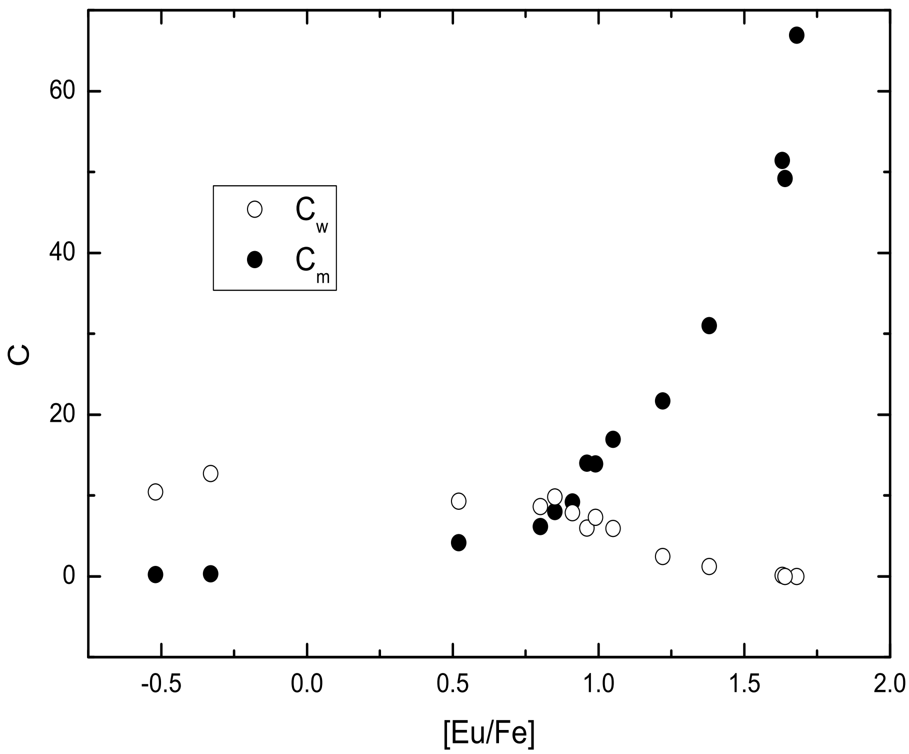

Figure 5. Component coefficients of weak r- and main r-process relative to the enrichment of Eu.

observed to be close to the solar pattern. It is well recognized that this apparent "universality" does not imply the existence of a single process for making all the nuclei in nature. However, based on our calculation, the overall solar r-pattern can be considered to have resulted from a mixture of these two types of r-process event.

The sites of weak r- and main r-process usually discussed was an explosive environment such as some region inside a core-collapse SN (Qian & wasserburg et al. 2007). Whether the elements of the Fe group and those of intermediate mass above N can be produced by a core-collapse SN is closely related to the pre-SN structure of the progenitor. There are two possible venues leading to a core-collapse SN: (1) collapse of an Fe core produced by progenitors of 12-25$M_{\odot}$, (2) collapse of an O-Ne-Mg core produced by progenitors of 8-11$M_{\odot}$. Observational data on low-metallicity stars in the Galactic halo show that sites producing the heavier neutron-capture nuclei do not produce Fe or any other elements between O and Zn. Insofar as a forming core-collapse SN is key to producing the heavy r-nuclei, then the mostly possible sources are SNe resulting from collapse of O-Ne-Mg cores, because they do not produce the elements of the Fe group or those of intermediate mass (above C and N). This suggests that the main r-process elements cannot be produced by massive stars of $> 11M_{\odot}$, which result in Fe core-collapse SNe and are sources for the elements from O to Zn (Woosley et al. 2002). On the other hand, the weak r-nuclei with A$\sim$90-110 are in general present in metal-poor stars with low abundances of heavier neutron-capture nuclei and produced in conjunction with the elements from O to Fe group elements (Qian & Wasserburg 2002, 2007; Izutani et al. 2009). Thus, this implies that the origins of weak r-process are Fe core-collapse SNe from progenitors of 12-25$M_{\odot}$, ejected most of their nucleosynthetic products, such as a host of nuclei from O to the Fe group(Qian & Wasserburg 2007). This has been shown to be possible in the calculated results of Izutani et al.(2009), which can reproduce the observational data of Sr, Y, and Zr in addition to the elements from O to Zn in weak r-process stars.

Using our calculated results, we discuss more thoroughly the mixing of weak r- and main r-process in the solar system. Assuming a Miller et al.(1979) initial mass function (IMF), the ratio of an Fe core-collapse SN event from a progenitor of 12-25$M_{\odot}$ to an O-Ne-Mg core-collapse SN event from a progenitor of 8-12$M_{\odot}$ is 0.797, which is approximately equal to calculated r-weak:r-main ratio for Sr, Y and Zr in the solar system. This means that a similar amount of lighter neutron-capture nuclei is produced per event for weak r- and main r-process venues. Thus, the yield of Sr per weak r-process event is estimated to be about $4.5 \times 10^{-6} M_{\odot}$, which is in good agreement with theoretical estimates from explosive nucleosynthesis calculations of weak r-process elements in extremely metal-poor core-collapse SN (Izutani et al. 2009). Obviously, in our picture, the ratio has a straightforward explanation in terms of the IMF. With the same IMF, we would find frequency ratios of 1.156, when taking 11 $M_{\odot}$ instead of 12$M_{\odot}$as the threshold between the two classes. Obviously, this estimate requires more stringent constraints on the masses from theoretical models and more accurate observed statistics.

It is interesting to define reduced component coefficients of metal-poor stars, C_w and C_m as:

$$N_i = (C_w N_{i,\ rw,\odot} + C_m N_{i,\ rm,\odot})10^{[Fe/H]}, \quad (4)$$

where $N_{i,\ rw,\odot} = C'_{w,\odot} N_{i,\ rw}$ and $N_{i,\ rm,\odot} = C'_{m,\odot} N_{i,\ rm}$. In equation (4), we choose the solar component coefficients as a standard and assume all of them are equal to 1. Note that the reduced component coefficient of metal-poor star gives the relative contribution of the individual process to that of solar system, normalized to the value of [Fe/H]. In fact, if we substitute $10^{[Fe/H]}$ with $Z/Z_\odot$ and assume $C_w = C_m = 1$, equation (4) will be returned to the r-process component of $N_{i,r} = N_{i,r,\odot} \times Z/Z_{r,\odot}$, which have used by Aoki et al. (2001).

4.4 Discussion of reduced Component Coefficients

The reduced component coefficients calculated are listed in the column (8) and (9) of Table 1. We can obtain important information about the neutron-capture nucleosynthesis from the reduced component coefficients, summed up as follows :

1. The component coefficients C_w and C_m represent the relative contributions from the weak r-process and the main r-process to the heavy element abundances, respectively. With them, we can accurately determine the relative contributions of the individual r-process to the neutron-capture element abundances in metal-poor stars and then compare them with the corresponding component coefficients of the solar system in which $C_w = C_m = 1$. Thus, $C_i > 1$ (i=r or m) means that, except for the effect of metallicity, the contributions from the corresponding r-process to the neutron-capture element abundances in metal-poor stars is larger than that in the solar system. $C_i < 1$ means that, except for the effect of the metallicity, the contributions from the corresponding r-process to the neutron-capture element abundances in metal-poor stars is less than that in the solar system. If C_w and C_m are not equal to each other, then the relative contribution from the weak r-process, the main r-process to the neutron-capture element abundances are not in the solar proportions.

2. From Table 1 we note that, for most sample stars except weak r-process stars and main r-process stars, both C_w and C_m are larger than unity. This means that the contributions from the weak r- and main r-process to the neutron-capture element abundances in these stars is larger than that in the solar system. Thus, similar to HD 221170, these stars can be called "weak r + main r stars".

3. By comparing the values of C_w and C_m, we can select those stars with special neutron-capture element abundance distributions and study them individually. If one component coefficient of one metal-poor star is much larger than another and larger than unity, this star might have been formed in a Galactic region that were not well mixed chemically and the corresponding neutron-capture process may be dominantly responsible for the neutron-capture elements in this star. In this case, we should consider only the contribution of this neutron-capture process to the abundances of neutron-capture elements in this star. For example, the ultra metal-poor halo star CS 22892-052 is a star of this situation. With our model, the component coefficients in this star are C_w=0.0, C_m=49.204, which mean that the main r-process is responsible for the synthesis of neutron-capture elements in the star. In Table 1 we can find that main r-process stars (i.e., CS 22892-052, CS 29497-004 and CS 31082-001) and weak r-process stars(i.e., HD 122563 and HD 88609) can be attributed to two different extreme categories. It should be noted that our model will be not effective for stars with higher metallicities ([Fe/H]$\gtrsim -1.6$), because the contribution from s-process cannot be ignore at this metallicity (Travaglio et al. 1999). The component coefficients C_w and C_m with [Eu/Fe], as illustrated in Figure 5, contain some interesting information for the enrichment of r-process in sample stars. Clearly, this figure reveals different groups that can be distinguished by the component coefficients.

Our model is based on the observed abundances of two main r-process stars and two weak r-process stars, and the observed abundances in metal-poor stars, so all the uncertainties of those observations will be involved in the model calculations, which results in the errors of the calculations and the uncertainties of the model. The errors of the calculations simply result from the measurement errors in those sample stars. These measurement errors are only reflected in equation (2) and can be estimated by the model. According to measurement errors of the abundance ratios in two main r-process stars and two weak r-process stars, we estimate that the typical errors of the model calculations are about ± 0.2 dex, because the errors of the model calculations are approximately equal to the measurement errors. Considering the uncertainties of the model calculations, one can find that there are more elements whose abundances are explained by the model predictions. However, we find that all these uncertainties cannot explain the larger errors of elements, such as Lu in BD +17°3248 and Ag in HD 221170. This implies that the understanding of the true patterns of the weak r-process and main r-process is incomplete for at least some of these elements.

5 CONCLUSIONS

The chemical abundances of the metal-poor star are an excellent test bed to set new constraints on models of neutron-capture processes at low metallicity. It did not appear that a straightforward ab initio solution to the r-process problem was within reach. On the other hand, a abundance-analysis approach based on the available observational data might offer some helpful guidance. Stars with low [Fe/H] values would provide important clues to whether and how core-collapse SNe are associated with the r-process. Based on the observation of metal-poor stars and neutron-capture element nucleosynthesis theory, we set up a model to determine the relative contributions from weak r- and main r-process to the neutron-capture element abundances in metal-poor stars. With this model we calculate the elemental abundances in 14 sample stars and the component coefficients C_w and C_m. Considering the Eu overabundance and excesses of lighter neutron-capture elements in most sample stars, it is worth to compare abundances of these stars with those of weak r-process stars and main r-process stars. Such study can provide clues for the understanding of the enrichment in neutron-capture elements of metal-poor stars, given that they should conserve the characteristics of r-process nucleosynthesis in massive stars in the early galaxy. The neutron-capture and light elements abundance pattern of most sample stars could be explained by a star formed in a molecular cloud that had ever been polluted by weak r- and main r-process material. Overall, the predicted abundances fit well the observed abundance patterns of these stars, from the light elements(O through Zn) and lighter neutron-capture elements (Sr through Ag), as well as heavier neutron-capture elements (Ba through Pb). We find that the main r-process source is responsible for the heavier neutron-capture elements such as Eu; and the light elements, such as Fe group, accompany with the weak r-process production, while both sources produce the lighter neutron-

capture elements. The main r-process elements nearly are not produced in conjunction with all light elements from O to Fe group elements, which is similar to the observed results of main r-process stars. The abundance pattern of light elements for the stars is very close to the pattern of weak r-process stars. This implies that these stars should be "weak r + main r star". The abundance, derived from the our model, are in excellent agreement with the observed values of sample stars, which means that the uniform and unique abundance pattern of weak r-process have extended to [Eu/Fe]$\approx$ 1.0, [Fe/H]≈ -2.1, and all observed elements.

In closing, we remind the reader that the results here have the virtue of being model independent, in that they do not refer to detailed r-process nucleosynthesis calculations. Of course, a full solution of the weak r-process will demand such calculations. Our hope is that the results here will provide a useful guide in interpreting those more complete r-process models. Our results give a constraint on the models of the r-process that yielded lighter and heavier neutron-capture elements in the early Galaxy. We look forward to a large data set on weak r- and main r-process abundances in very low metallicity stars, which will improve our understanding of weak r- and main r-process nucleosynthesis in the early Galaxy.

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